REDUCED-TANTALUM SUPERALLOY COMPOSITION OF MATTER AND ARTICLE MADE THEREFROM, AND METHOD FOR SELECTING A REDUCED-TANTALUM SUPERALLOY

[0001] This invention relates to a composition of matter suitable for use in aggressive, high-temperature gas turbine environments, and articles made therefrom.

BACKGROUND OF THE INVENTION

[0002] Nickel-base superalloys are alloys having more nickel than any other element, and containing a group of elements that produce gamma-prime and related precipitates during an appropriate heat treatment. Nickel-base superalloys are the currently preferred alloy choice for making the components of aircraft-gas turbine engines that are exposed to the highest temperatures. Examples include turbine blades, turbine vanes, some shafts, some rotors, interstage seals, and many high-temperature stationary gas-path components.

[0003] The nickel-base superalloys must exhibit acceptable mechanical properties at both low and high temperatures, such as good strength, good fatigue resistance, low creep rates, sufficient ductility, and acceptable density. They must also have good corrosion and oxidation resistance in the harsh combustion-gas environment. Further, the superalloys must have good stability in both extended exposure at elevated temperature and cyclic heating and cooling patterns. These properties are achieved through the careful selection of the alloying elements and the processing of the material. A number of superalloy compositions have been developed to supply the appropriate combinations of these properties for various applications in the gas turbine environment.

[0004] Additionally, the cost of the superalloy material is a consideration. While achieving the required properties is of paramount concern, the manufacture and sales of gas turbine engines is a competitive business. Some of the elements used in the nickel-base superalloys are rather exotic in nature and costly, and

therefore their presence and amount is an important factor in the cost of the gas turbine engine. Further, some elements are subject to periodic shortages wherein the price becomes almost prohibitively high.

[0005] In the work leading to the present invention, the inventors recognized that one such element that is used in advanced nickel-base superalloys is tantalum. An important nickel-base superalloy used in gas turbine blades and other applications, Rene™ N5, contains a nominal 6.2 weight percent tantalum, and other nickel-base superalloys contain 5 percent or more of tantalum. In the last several years, the price of tantalum of the quality required for use in nickel-base superalloys increased from about $100 per pound to $475 per pound, with some projections of even higher price based on worldwide shortages. Other economic forces have temporarily lowered the price, but there is a future potential for comparable price increases and shortages. The high prices and potential shortages thus threaten the continued economic viability and availability of articles made of such materials.

[0006] There is accordingly a need for improved nickel-base superalloys with properties comparable with existing high-tantalum nickel-base superalloys such as Rene™ N5, but which are not as dependent upon the use of high percentages of tantalum. The present invention fulfills this need, and further provides related advantages.

SUMMARY OF THE INVENTION

[0007] The present invention provides a nickel-base superalloy and articles made from the nickel-base superalloy, and an approach for selecting and designing nickel-base superalloys. The nickel-base superalloy contains a reduced nominal tantalum content as compared with higher-tantalum alloys, and with corresponding modifications of other alloying elements to provide the comparable performance of the higher-tantalum alloys.

[0008] An article comprises a composition consists essentially of, in weight percent, from about 4 to about 12 percent cobalt, from about 3.5 to about 7 percent tungsten, from about 2 to about 9 percent chromium, from about 0.5 to about 4.5

percent tantalum, from about 5.5 to about 7.5 percent aluminum, from 0 to about 5.5 percent rhenium, from about 0.1 to about 1.2 percent titanium, from 0 to about 3 percent molybdenum, from 0 to about 3 percent ruthenium, from about 0.5 to about 2 percent columbium, about 0.01 percent maximum boron, about 0.07 percent maximum carbon, from about 0.3 to about 1 percent hafnium, about 0.01 percent maximum zirconium, about 0.03 percent maximum yttrium, from 0 to about 0.5 percent vanadium, about 0.01 percent maximum cerium, and about 0.01 percent maximum lanthanum, balance nickel and impurity elements. Most preferably, the article includes from about 3.0 to about 4.0 percent tantalum.

[0009] In one preferred form, the article includes from about 3.0 to about 4.0 percent tantalum, from about 0.2 to about 0.4 percent titanium, from about 0.5 to about 0.7 percent hafnium, and from about 1 to about 2 percent columbium. In another preferred form, the article includes from about 6 to about 12 percent cobalt, from about 4.5 to about 6.5 percent tungsten, from about 5.5 to about 6.5 percent chromium, from about 3.0 to about 4 percent tantalum, from about 5.8 to about 6.3 percent aluminum, from about 2.8 to about 3.5 percent rhenium, from about 0.2 to about 0.4 percent titanium, from about 1.3 to about 1.7 percent molybdenum, from about 0.5 to about 0.7 percent hafnium, and from about 1 to about 2 percent columbium. In a most-preferred form, the article includes from about 7 to about 10 percent cobalt, from about 6 to about 6.3 percent tungsten, about 6 percent chromium, from about 3.1. to about 3.5 percent tantalum, from about 5.9 to about 6.3 percent aluminum, about 0.3 percent titanium, about 0.6 percent hafnium, about 3 percent rhenium, about 1.5 percent molybdenum, and about 1.5 percent columbium.

[0010] Desirably, the article is substantially a single crystal or a directionally oriented polycrystal produced by directional solidification. It is preferably shaped as a component of a gas turbine engine, such as a gas turbine blade.

[0011] A related composition of matter consists essentially of, in weight percent, from about 4 to about 12 percent cobalt, from about 3.5 to about 7 percent tungsten, from about 2 to about 9 percent chromium, from about 0.5 to about 4.5 percent tantalum, from about 5.5 to about 7.5 percent aluminum, from 0 to about

5.5 percent rhenium, from about 0.1 to about 1.2 percent titanium, from 0 to about 3 percent molybdenum, from 0 to about 3 percent ruthenium, from about 0.5 to about 2 percent columbium, about 0.01 percent maximum boron, about 0.07 percent maximum carbon, from about 0.3 to about 1 percent hafnium, about 0.01 percent maximum zirconium, about 0.03 percent maximum yttrium, from 0 to about 0.5 percent vanadium, about 0.01 percent maximum cerium, and about 0.01 percent maximum lanthanum, balance nickel and impurity elements. Preferred and most-preferred compositions as discussed elsewhere herein are applicable to the composition of matter.

[0012] The present invention also provides an approach for extending the principles used to develop the above-described composition to the modification of other nickel-superalloys to reduce their tantalum contents.. A method for selecting a reduced-cost nickel-base superalloy comprises the steps of identifying a baseline nickel-base superalloy having a nominal composition, in weight percent, comprising a baseline tantalum content of more than about 5 weight percent tantalum, and a baseline sum (baseline hafnium content plus baseline columbium content plus baseline titanium content plus baseline tungsten content), in weight percent. (Calculated quantities are enclosed in parentheses for clarity herein.) The method further includes selecting a modified nickel-base superalloy having a nominal composition, in weight percent, comprising a modified tantalum content at least 1.5 weight percent less than the baseline tantalum content, and a modified baseline sum of (modified hafnium content plus modified columbium content plus modified titanium content plus modified tungsten content) at least 1.5 weight percent greater than the baseline sum.

[0013] That is, the reduction in tantalum content for cost reasons must be compensated for by increasing the sum of hafnium, columbium, titanium, and tungsten. Preferably, the increase in the sum of hafnium, columbium, titanium, and tungsten is at least as great as the decrease in the tantalum content. That is, the absolute value of (the modified baseline sum minus the baseline sum) is preferably at least as great as the absolute value of (the modified tantalum content minus the baseline tantalum content). It is also preferred that the modified nickel-base superalloy have a nonzero modified hafnium content, a nonzero modified

columbium content, a nonzero modified titanium content, and a nonzero modified tungsten content. Desirably, the sum of the modified tungsten content plus a modified molybdenum content is at least about 6.5 weight percent, for most modified nickel-base superalloys.

[0014] Commercial baseline nickel-base superalloys such as PWA 1484, Rene™ 142, and the CMSX alloys such as CMSX-4 and CMSX-10 may be modified according to these principles to reduce their tantalum contents while maintaining acceptable properties.

[0015] The present article, especially in its preferred and most-preferred forms, exhibits performance comparable with that of higher-tantalum alloys, but with a reduced tantalum content, and consequently a reduced cost. The cost savings becomes highly significant when tantalum prices exceed several hundred dollars per pound, as has been the case recently and which may occur again in the future. Other features and advantages of the present invention will be apparent from the following more detailed description of the preferred embodiment, taken in conjunction with the accompanying drawings, which illustrate, by way of example, the principles of the invention. The scope of the invention is not, however, limited to this preferred embodiment.

BRIEF DESCRIPTION OF THE DRAWINGS

[0016] Figure 1 is a perspective view of a gas turbine blade;

[0017] Figure 2 is a block flow diagram of a method for fabricating the article of Figure 1; and

[0018] Figure 3 is a bar chart of oxidation weight loss in cyclic oxidation tests, for the tested alloys.

DETAILED DESCRIPTION OF THE INVENTION

[0019] Figure 1 depicts a component article 20 of a gas turbine engine, illustrated as a gas turbine blade 22. The gas turbine blade 22 includes an airfoil 24, an attachment 26 in the form of a dovetail to attach the gas turbine blade 22

to a turbine disk (not shown), and a laterally extending platform 28 intermediate the airfoil 24 and the attachment 26. In one preferred embodiment, the component article 20 is substantially a single crystal. That is, the component article 20 is at least about 80 percent by volume, and more preferably at least about 95 percent by volume, a single grain with a single crystallographic orientation. There may be minor volume fractions of other crystallographic orientations and also regions separated by low-angle boundaries. The single-crystal structure is prepared by the directional solidification of an alloy composition as discussed herein, usually from a seed or other structure which induces the growth of the single crystal and single grain orientation. In another preferred embodiment, the component article 20 is a directionally oriented polycrystal, in which there are at least several grains all with a commonly oriented preferred growth direction. The directionally oriented polycrystal is produced by directional solidification, typically without a seed.

[0020] The use of the alloy composition discussed herein is not limited to the gas turbine blade 22, and it may be employed in other articles such as gas turbine vanes, or articles that are not to be used in gas turbine engines.

[0021] Figure 2 is a block-flow diagram of a preferred approach for practicing the invention. The alloying elements that form the nickel-base alloy are provided in the proper proportions and melted together to form the molten alloy, step 40. In a specific form, the alloy has a composition consisting essentially of, in weight percent, from about 4 to about 12 percent cobalt, from about 3.5 to about 7 percent tungsten, from about 2 to about 9 percent chromium, from about 0.5 to about 4.5 percent tantalum, from about 5.5 to about 7.5 percent aluminum, from 0 to about 3.5 percent rhenium, from about 0.1 to about 1.2 percent titanium, from 0 to about 3 percent molybdenum, from 0 to about 3 percent ruthenium, from about 0.5 to about 2 percent columbium, about 0.01 percent maximum boron, about 0.07 percent maximum carbon, from about 0.3 to about 1 percent hafnium, about 0.01 percent maximum zirconium, about 0.03 percent maximum yttrium, from 0 to about 0.5 percent vanadium, about 0.01 percent maximum cerium, and about 0.01 percent maximum lanthanum, balance nickel and impurity elements. (All compositional percentages herein are stated in weight percent, unless indicated to the contrary.)

[0022] Preferably, the alloy includes from about 3.0 to about 4.0 percent tantalum. In one preferred form, the article includes from about 3.0 to about 4.0 percent tantalum, from about 0.2 to about 0.4 percent titanium, from about 0.5 to about 0.7 percent hafnium, and from about 1 to about 2 percent columbium. In another preferred form, the article includes from about 6 to about 12 percent cobalt, from about 4.5 to about 6.5 percent tungsten, from about 5.5 to about 6.5 percent chromium, from about 3.0 to about 4 percent tantalum, from about 5.8 to about 6.3 percent aluminum, from about 2.8 to about 3.5 percent rhenium, from about 0.2 to about 0.4 percent titanium, from about 1.3 to about 1.7 percent molybdenum, from about 0.5 to about 0.7 percent hafnium, and from about 1 to about 2 percent columbium. In a most-preferred form, the article includes from about 7 to about 10 percent cobalt, from about 6 to about 6.3 percent tungsten, about 6 percent chromium, from about 3.1. to about 3.5 percent tantalum, from about 5.9 to about 6.3 percent aluminum, about 0.3 percent titanium, about 0.6 percent hafnium, about 3 percent rhenium, about 1.5 percent molybdenum, and about 1.5 percent columbium.

[0023] Most high performance superalloys for the most-demanding applications contain at least about 5-6 weight percent tantalum, and in some cases considerably more tantalum. The present invention desirably reduces the tantalum content of the alloy of the invention to no more than about half the initial amount in the baseline nickel-base superalloy, and typically less than about 4 weight percent. The resulting superalloy, with adjustments of other alloying proportions, has acceptable performance and also a cost which is significantly less than that of comparable superalloys, an important consideration at times when the cost of tantalum is high.

[0024] The tantalum in the gamma-prime hardened superalloy is an important ingredient because tantalum is a heavy refractory which can replace aluminum in the Ni_3Al-based gamma-prime strengthening phase. The tantalum has a secondary effect of improved castability with respect to grain defects by balancing out the density differences between the first and last liquid to solidify (i.e., between the dendrite core and the interdendritic regions). The presence of tantalum also does not have a negative effect on environmental resistance in

respect to oxidation and hot corrosion, unlike other refractory metals such as molybdenum and tungsten. Thus, reducing the tantalum content below about 5 weight percent, while retaining strength and environmental-resistance properties is challenging.

[0025] In the present approach, tantalum may be replaced by columbium and/or hafnium and/or titanium and/or tungsten on the gamma-prime aluminum sites. The tungsten partitions to both the gamma phase and to the gamma prime phase, so that it aids in increasing the strength of the gamma prime phase as well as the gamma matrix. However, an excessively large increase in the tungsten content tends to lead to phase instability in the alloy over long exposure to elevated temperature, and therefore the tungsten content is limited.

[0026] The present alloy contains from about 0.5 to about 4.5 percent tantalum, more preferably from about 3 to about 4 percent, and most preferably from about 3.1 to about 3.5 percent. If the tantalum content is less than about 0.5 percent, the alloy has insufficient strength. If the tantalum content is less than about 2.5 percent, the strength is unsatisfactory for many applications, and the article is prone to casting defects. If the tantalum content is more than about 4.5 percent, the alloy cost becomes prohibitive as the cost of tantalum increases. Also, a tantalum content of greater than about 4 percent, with the present levels of columbium, titanium, and hafnium, produces a nickel-base superalloy with too much gamma prime phase and resulting instability.

[0027] The alloy contains from about 0.1 to about 1.2 percent titanium. Titanium is a potent gamma prime hardener, and at least about 0.1 percent must be present in order to compensate for the reduced tantalum content. The optional titanium addition substitutes for aluminum and tantalum in the gamma prime phase, improving the strength. However, higher levels of titanium adversely affect oxidation resistance.

[0028] The alloy contains from about 0.3 to about 1 percent hafnium. Hafnium improves the oxidation and hot corrosion resistance of coated alloys, but can degrade the corrosion resistance of uncoated alloys. Hafnium also improves the life of thermal barrier coatings, where used. Experience with other alloys has shown that hafnium contents on the order of 0.75 percent are satisfactory.

However, when the hafnium content exceeds about 1 percent, the stress rupture properties are reduced and the incipient melting temperature is reduced.

[0029] The alloy contains from about 0.5 to about 2 percent columbium (also sometimes termed "niobium"), which substitutes for tantalum in the gamma prime phase. Lesser amounts result in insufficient amounts and strength of the gamma prime phase. Greater amounts excessively reduce the gamma-prime solvus temperature and reduce oxidation resistance.

[0030] The alloy contains from about 4 to about 12 percent cobalt. Lesser amounts result in reduced alloy stability. Greater amounts reduce the gamma prime solvus temperature and thus the high-temperature strength, and impair the oxidation resistance.

[0031] The alloy contains from about from about 3.5 to about 7 percent tungsten. Lesser amounts unacceptably decrease the strength of the superalloy, and greater amounts produce instability with respect to TCP (topologically close packed) phase formation.

[0032] The alloy contains from about 2 to about 9 percent chromium. Lesser amounts reduce hot corrosion resistance while greater amounts lead to phase instability and poor cyclic oxidation resistance.

[0033] The alloy contains from about 5.5 to about 7.5 percent aluminum. Lesser amounts reduce strength due to a reduction in the gamma prime phase. Greater amounts produce instability with respect to TCP phase formation and incipient melting problems during alloy heat treatment.

[0034] The alloy contains from 0 to about 5.5 percent rhenium, more preferably from 0 to about 3.5 percent rhenium, even more preferably from about 2.8 to about 3.5 percent rhenium, and most preferably about 3 percent rhenium. Greater amounts produce alloy instability with respect to TCP phase formation.

[0035] The alloy contains from 0 to about 3 percent ruthenium. Greater amounts reduce oxidation resistance and do not improve alloy stability.

[0036] The alloy contains about 0.01 percent maximum boron, preferably about 0.006 percent maximum boron. Greater amounts cause incipient melting problems during alloy heat treatment.

[0037] The alloy contains about 0.07 percent maximum carbon. The

carbon is a deoxidizer to reduce inclusions. Greater amounts sap the strength of the superalloy by chemically combining to form carbides of hardening elements. The carbides also serve as the sites for fatigue failure initiation.

[0038] The alloy contains about 0.01 percent maximum zirconium. Greater amounts cause incipient melting problems during alloy heat treatment.

[0039] The alloy contains about 0.03 percent maximum yttrium. Greater amounts promote undesirable mold-metal reaction at the casting surface and increase the inclusion content of the cast article.

[0040] The alloy contains from 0 to about 0.5 percent vanadium. Greater amounts reduce the hot corrosion resistance of the alloy.

[0041] The alloy contains about 0.01 percent maximum cerium and about 0.01 percent maximum lanthanum. Greater amounts of either of these elements promote an undesirable mold-metal reaction at the casting surface and increase the inclusion content of the component.

[0042] The alloy preferably contains about 0.1 percent maximum silicon. Silicon in such minor amounts may aid oxidation resistance.

[0043] The alloy preferably contains about 0.04 percent maximum magnesium and about 0.01 percent maximum calcium as de-oxidizers. These elements in small quantities may also improve the oxidation resistance.

[0044] The balance of the alloy is nickel and impurity elements. The nickel content is preferably in the range of from about 61 to about 64 weight percent.

[0045] Studies and calculations were performed to establish limits for the various elements. The following Table I sets for the compositions of alloys actually melted. Alloys E1-E18 are alloys within the scope of the present invention, and alloy RN5 is commercial Rene™ N5 alloy, which is not within the scope of the invention.

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Table I

No.	Al	Ta	Cr	W	Cb	Co	Ti	Hf	Y	Ni
E1	6.25	3.5	6	5	1	10	0	0.15	0.015	63.5
E2	6.25	3.5	6	6	1	10	0	0.15	0.015	62.5
E3	6.25	3.5	6	5	1.5	10	0	0.15	0.015	63.0
E4	6.25	3.5	6	6	1.5	10	0	0.15	0.015	62.0
E5	6.25	3.5	6	5	1	10	0	0.6	0.015	63.1
E6	6.25	3.5	6	6	1	10	0	0.6	0.015	62.1
E7	6.25	3.5	6	5	1.5	10	0	0.6	0.015	62.6
E8	6.25	3.5	6	6	1.5	10	0	0.6	0.015	61.6
E9	6.25	3.5	6	6	1	10	0.3	0.15	0.015	62.2
E10	6.25	3.5	6	5	1.5	10	0.3	0.15	0.015	62.7
E11	6.25	3.5	6	5	1	10	0.3	0.6	0.015	62.8
E12	6.25	3.5	6	6	1.5	10	0.3	0.6	0.015	61.3
E13	6.22	3.5	6	6.5	1.5	10	0	0.15	0.015	61.5
E14	6.22	3.5	6	6.5	1.0	10	0	0.6	0.015	61.5
E15	6.25	4.0	6	5.5	1.3	10	0	0.15	0.015	62.1
E16	6.60	3.5	6	5.5	1.0	10	0.3	0.15	0.015	62.4
E17	6.20	3.5	7	5	1.5	10	0.3	0.15	0.015	61.8
E18	6.20	3.5	7	5	2.0	10	0.3	0.15	0.015	61.3
RN5	6.2	6.5	7	5	0	7.5	0	0.15	0	63.1

[0046] For these alloys, in all cases the Mo content was 1.5 weight percent, the Re content was 3 weight percent, the Ru content was 0, and the carbon content was 0.05 weight percent.

[0047] Compositional and property computed values for the alloys are set forth in Table II. The value of ΔTa is the change in tantalum content for the

indicated alloy as compared with RN5. The value of Δ(Ti+Hf+Cb+W) is the change in the computed sum for the indicated alloy as compared with RN5. The value of (W+Mo) is the numerical sum of these two elements.

Table II

No.	ΔTa	Δ(Ti+Hf+Cb+W)	(W + Mo)	Density
E1	-3.0	1.0	6.5	0.309
E2	-3.0	2.0	7.5	0.311
E3	-3.0	1.5	6.5	0.310
E4	-3.0	2.5	7.5	0.311
E5	-3.0	1.5	6.5	0.309
E6	-3.0	2.5	7.5	0.311
E7	-3.0	2.0	6.5	0.310
E8	-3.0	3.0	7.5	0.311
E9	-3.0	2.3	7.5	0.310
E10	-3.0	1.8	6.5	0.309
E11	-3.0	1.8	6.5	0.309
E12	-3.0	3.3	7.5	0.311
E13	-3.0	3.0	8.0	0.313
E14	-3.0	2.9	8.0	0.312
E15	-2.5	1.8	7.0	0.311
E16	-3.0	1.8	7.0	0.308
E17	-3.0	1.8	6.5	0.309
E18	-3.0	2.3	6.5	0.309
RN5	0	0	6.5	0.312

[0048] Creep Rupture tests were performed for these alloys. The

temperatures, times, and number of hours to failure are shown in Table III:

Table III

No.	2100°F, 11ksi	2000°F, 18ksi	1800°F, 35ksi	1600°F, 75ksi
E1	20.0	32.7	69.8	40.8
E2	47.3	114.4	118.1	123.9
E3	40.9	61.1	114.6	95.9
E4	67.6	100.9	147.1	162.3
E5	23.7	42.1	76.9	48.4
E6	34.1	68.1	99.7	79.1
E7	52.5	68.6	120.6	95.3
E8	75.1	97.3	120.4	139.5
E9	42.7	80.4	105.2	102.1
E10	34.3	53.3	88.6	40.0
E11	61.6	58.2	106.0	81.8
E12	217.3	165.9	132.9	205.9
E13	42.7	83.7	123.5	100.2
E14	46.7	87.9	102.9	75.0
E15	61.9	82.7	130.5	211.8
E16	180.9	98/76.5	127.5	174.4
E17	33.0	62.5	96.5	93.5
E18	86.3	85.6	118.5	174.7
RN5	104.3	147	150.5	182.2

[0049] The approach taken in the alloy development was to replace tantalum with columbium and/or hafnium and/or titanium and/or tungsten on gamma prime aluminum sites, and to provide tungsten for additional gamma solid

solution strengthening. A slight chromium reduction was made to offset the tungsten increase to maintain alloy stability. The alloy compositions set forth in Table I were evaluated. The compositions E1-E12 represent two designed experiments, to establish the effects of tungsten, columbium, hafnium, and titanium modifications. Alloys E1-E8 are a full factorial in tungsten, columbium, and hafnium, while alloys E1, E4, E6-7, and E9-12 are a $2^{4+1}{}_{IV}$ experiment to economically understand the effects of titanium modifications. Alloys E8 and E12 have the same tungsten, columbium, and hafnium contents, but alloy E12 has 0.3 percent titanium, with the result that the mechanical performance of alloy E12 is substantially improved over that of alloy E8.

[0050] Small lab scale heats were vacuum melted for each composition. The melts were subsequently directionally solidified into columnar grained specimens to form directionally oriented polycrystals and tested in the longitudinal direction. Because the grain boundaries are parallel to the stress direction in the testing, the effect of the grain boundaries is minor. Alloy RN5 has the nominal composition of Rene™ N5 alloy.

[0051] Based upon the testing, composition E12 was selected as the preferred alloy composition, and acceptable variations were defined for specific applications as set forth above. Some specific alloys of interest include:

Table IV

Alloy No.	Al	Ta	W	Co	Hf
Y-1716	6.25	3.5	6.0	10	0.60
Y-1717	6.25	3.5	6.0	7.5	0.60
Y-1718	6.20	3.25	6.25	10	0.50

[0052] For these alloys, in all cases the Cr content was 6.0 weight percent, the Mo content was 1.5 weight percent, the Re content was 3 weight percent, the columbium content was 1.5 percent, the carbon content was 0.03 weight percent, and the boron content was 0.004 weight percent. Three hundred pound heats of each of these alloys of Table IV were prepared for evaluation.

[0053] Cyclic oxidation tests, with 20 cycles per hour for 103 hours to 2200°F and in a Mach 1.0 gas flow were performed and the weight losses measured. The results are illustrated in Figure 3.

[0054] Returning to the discussion of Figure 2, the melted alloy is solidified to form an article, step 42. The solidification may be of any operable type, such as a multidirectional heat flow to produce an unoriented polycrystalline article, a substantially uniaxial directional solidification to produce a directionally oriented polycrystalline article, or a uniaxial solidification with a seed, constriction, or other approach to producing a substantially single crystal article.

[0055] The solidified article may optionally be post processed, step 44, by any operable approach. Post processing may include, for example, cleaning, coating, grinding, machining, and the like.

[0056] The approach just described has defined a low-tantalum modification of the baseline Rene™ N5 nickel-base superalloy. Low-tantalum modifications of other baseline nickel-base superalloys may be made using the same principles. In one approach, a reduced-cost nickel-base superalloy is selected by first identifying a baseline nickel-base superalloy having a nominal composition, in weight percent, comprising a baseline tantalum content of more than about 5 weight percent tantalum, and a baseline sum (baseline hafnium content plus baseline columbium content plus baseline titanium content plus baseline tungsten content), in weight percent. A number of baseline nickel-base superalloys are candidates for the application of the present approach, because of their high tantalum contents. Examples of such commercial baseline nickel-base superalloys include PWA 1484 (nominally 8.7 percent tantalum), Rene™ 142 (nominally 6.35 percent tantalum), and the CMSX alloys such as CMSX-4 (nominally 6.5 percent tantalum) and CMSX-10 (nominally 7.5 percent tantalum) may be modified according to these principles to reduce their tantalum contents while maintaining acceptable properties.

[0057] A modified nickel-base superalloy is selected having a nominal composition, in weight percent, comprising a modified tantalum content at least 1.5 weight percent less than the baseline tantalum content, and a modified baseline sum of (modified hafnium content plus modified columbium content plus

modified titanium content plus modified tungsten content) at least 1.5 weight percent greater than the baseline sum. It is preferred that the increase in the sum of hafnium, columbium, titanium, and tungsten contents be at least as great as the decrease in the tantalum content. It is also preferred that the modified nickel-base superalloy has a nonzero modified hafnium content, a nonzero modified columbium content, a nonzero modified titanium content, and a nonzero modified tungsten content; that is, all of these elements should be present in nonzero amounts. The data also shows that the sum of the modified tungsten content plus a modified molybdenum content in the modified nickel-base superalloy should be at least about 6.5 weight percent.

[0058] Other features and advantages of the present invention will be apparent from the following more detailed description of the preferred embodiment, taken in conjunction with the accompanying drawings, which illustrate, by way of example, the principles of the invention. The scope of the invention is not, however, limited to this preferred embodiment.